SNOWPACK WATER CONTENT BY REMOTE SENSING

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SUMMARY

Snowpack water content by remote sensing is described, based on plane-layered models consisting of air, snow, ice, water, and earth. The reflection coefficient has been computed for a normally incident plane electromagnetic wave at frequencies between 10^6 to 10^{10} Hz. An example of the theoretical results is given, showing how the water content of the snow layer and thickness of the ice can be obtained from the shape of the curve of reflection coefficient versus frequency. An approximate explanation in terms of a three-layer model is given. Results are given for an illustrative field test. The paper also briefly reviews other systems for electromagnetic remote sensing and discusses snow electrical properties. Possible airborne applications of the proposed electromagnetic system are outlined.

RESUME

Une méthode, basée sur un modèle de couche plane consécutive d'air, de neige, de glace, d'eau et de terre, pour déterminer à distance, la quantité d'eau contenue dans la neige est décrite. Le coefficient de réflexion est calculé dans le cas d'une onde plane électromagnétique, de fréquence comprise entre 10^6 et 10^{10} Hz, en incidence normale. Un calcul théorique est donné, montrant comment la quantité d'eau contenue dans la neige, et l'épaisseur de la couche de glace, peuvent être obtenus à partir de la forme de la courbe du coefficient de réflexion en fonction de la fréquence. Une description utilisant un modèle à trois couches est donnée. Les résultats sont donnés pour illustrer un test réel. La publication donne aussi une brève revue d'autres systèmes de détection à distance utilisant une onde électromagnétique, et discute les propriétes électriques de la neige. Les applications possibles, à partir d'avion, du système proposé, de détection par onde électromagnétique, sont presentées.

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Background

Measurement of snowpack water content is evidently very important for the management of water resources in many regions of the world. At present, trained operators traverse snow courses to obtain snow depth and density. Another method employs a "pressure pillow" to weigh the snow above it. Recently, attention has been given to systems involving attenuation of gamma rays caused by absorption in a snow layer; artificial sources placed beneath the snow can be employed as well as the natural radioactivity of the earth. Although the methods in current use have proved to be of great value in providing information to permit forecasting of water runoff, each depends on "point" measurements; that is, the individual readings at the stations must be combined by statistical methods to yield a net value. Methods that could encompass larger regions on a reasonably periodic basis appear to be desirable. Photography from airplane or satellite represents an excellent example of large-scale information regarding the extent of snow cover. However, large-area photography does not provide information regarding snow depth and density. The NASA Earth Resources Survey Program (1967) recognized that: "An airborne or spaceborne sensor that could map synoptically the water content and thickness of snow would be immensely valuable" [1].

Three electromagnetic remote sensing examples are summarized here. Echo depth sounding of polar ice sheets from airplanes was accomplished by Evans and Smith [2], using a pulse-modulated radar system having a carrier frequency of 35 MHz. They quote a resolution of 10 meters in measured depth of ice. Snowfield mapping with airborne K-band imaging radar was accomplished by Waite and MacDonald [3], who found an "anomalously high signal return from old snow." Because ground truth was not available for comparison with their results, they suggest that "the use of additional sensor frequencies and the relative penetration of each should certainly be investigated as a means of monitoring the volume and quality of snowfields and ice fields." An investigation was made by Cumming [4] to obtain the permittivity and loss tangent of snows of varying density, temperature, and water content, and also to measure the reflection coefficient of snow-covered surfaces. All of his measurements were made at a free-space wavelength of 3.2 cm. The reflection coefficient was found to be predominantly caused by the air-snow interface, for snow layers more than a few wavelengths thick.

The dielectric constant (or permittivity) and loss tangent are the most important of the basic electrical properties of snow that affect its electromagnetic response. The dielectric constant and density of snow can be related by the widely used Weiner [5] theory of dielectric mixtures:

$$\frac{\varepsilon_m-1}{\varepsilon_m+u} = p\left(\frac{\varepsilon_1-1}{\varepsilon_1+u}\right) + (1-p)\left(\frac{\varepsilon_2-1}{\varepsilon_2+u}\right)$$

where ε_m, ε_1, and ε_2 are the dielectric constants of snow, ice, and air, respectively; p is the proportion of the total volume occupied by the ice; and u is the parameter called the Formzahl, which characterizes the structure of the mixture. Numerical values of the Formzahl in practice can range from 2 (for an aggregate of spherical particles) to infinity (for highly elongated particles oriented essentially parallel). Curves for ε_m versus density corresponding to Formzahl numbers of 2 and infinity are shown by dashed lines in Fig. 1. A solid-line curve is shown corresponding to the Formzahl number $u = 3$, and points are plotted representing data given in Cumming's publication [4]. The excellent agreement suggests that a system that can measure the dielectric constant of dry snow may thereby determine the density, within acceptable limits.

The loss tangent of snow is very dependent on the percent of liquid water present. A value for loss tangent for a specific snow may be inapplicable by several orders of magnitude for other snows with different amounts of liquid water. To take this fact into account on a realistic basis, five different types of snow were postulated, for calculations to be described below, having loss-tangent variation with frequency as shown in Fig. 2, so as to encompass all real snow types. Curve 5 of Fig. 2 approximates the experimental values for a "dry" snow, given by Yoshino [6]. For "wet" snow, having much higher values of loss tangent, curves 1 and 2 represent about as extreme values as would be encountered.

Theoretical Basis for Proposed System

The proposed system is a direct "spin-off" from some of the basic research in the NASA space exploration program. Theoretical analyses and computer codes were used to obtain the response of (hypothetical) plane layers on the moon, assuming incident plane electromagnetic waves, as described by Linlor, Ward, and Jiracek [7,8]. The application of this computer code to various layered models of snow, ice, water, and earth was quite reasonable, although initially it was not at all clear that useful results would be obtained in the new situation. In particular, the electrical parameters of snow, in situ, are known to cover a wide range of values depending on the density, temperature, free-water content, and other variables such as sequences of rain, freezing, etc. Clearly, the theoretical calculations would at best serve as guides, and require field testing versus ground truth for convincing evidence.

The following is an outline of the theory for the calculations. The complex plane wave impedance Z for an $\exp(i\omega t)$ time dependence of a homogeneous, nonmagnetic half-space is $Z = |Z| \exp(i\phi) = i\mu_0\omega/\gamma$, where ϕ is the phase and $|Z|$ the modulus of Z, ω is the angular frequency, μ_0 the magnetic permeability of free space, γ the wave number of the half-space. The wave number is $\gamma = [i\mu_0\omega(\sigma+i\epsilon\omega)]^{1/2}$ in which the permittivity ϵ and the conductivity σ are real functions of frequency. The loss tangent is defined by $\tan \delta = \sigma/\omega\epsilon$. The amplitude reflection coefficient for normal incidence is $r = (Z-Z_o)/(Z+Z_o)$, where Z_o is the plane-wave impedance of free space. At high frequencies such that $(\sigma/\omega\epsilon) << 1$, γ is imaginary so that Z and r are real. For n layers we may use the formulation of Wait [9]:

$$Z_a = Z_1 \frac{\hat{Z}_2 + Z_1 \tanh \gamma_1 h_1}{Z_1 + \hat{Z}_2 \tanh \gamma_1 h_1}$$

$$\hat{Z}_2 = Z_2 \frac{\hat{Z}_3 + Z_2 \tanh \gamma_2 h_2}{Z_2 + \hat{Z}_3 \tanh \gamma_2 h_2}$$

$$\hat{Z}_{n-1} = Z_{n-1} \frac{\hat{Z}_n + Z_{n-1} \tanh \gamma_{n-1} h_{n-1}}{Z_{n-1} + \hat{Z}_n \tanh \gamma_{n-1} h_{n-1}} ,$$

where $Z_j = i\mu_0\omega/\gamma_j$ is the characteristic impedance of the jth layer; $\hat{Z}_j$ is the impedance at the top of the jth layer, and Z_a is the surface impedance of the structure, equal at any given frequency to the impedance of an equivalent homogeneous half-space. The h_j are the thicknesses of the layers in the structure. The nth layer is semi-infinite; therefore, $\hat{Z}_n = Z_n$. The amplitude reflection coefficient for an n-layered structure is therefore:

$$r = (Z_a - Z_o)/(Z_a + Z_o) .$$

Implicit in the preceding analysis are the assumptions of normal incidence of plane waves, specular reflection, homogeneity within layers, and abrupt boundaries between interfaces (i.e., small compared with the incident wavelength). In the "real-world" situation, many factors are present that may conflict, in varying degree, with the above assumptions, such as the presence of trees, vegetation, and surface roughness, subsurface scatterers (such as large boulders), reflection from subsurface earth layers, non-normal reflection planes from side structures, etc. The theoretical results to be given must therefore be interpreted with these assumptions and limitations clearly understood. To be applicable for snow depth and density determination, the assumed electrical properties should be reasonable approximations to the actual values.

Models as indicated in Fig. 3 involving air, snow, ice, water, and earth have been analyzed for five types of snow, ranging from very dry to very wet, with three representative values of snow dielectric constant (and therefore density). The results are far too extensive to be included in this paper, and are to be published elsewhere [10]; only one example will be given here, as shown in Fig. 4. This gives the reflection amplitude versus frequency for a model having snow thickness of 91.4 cm (3 ft), ice thickness of 7.56 cm (3 in.), and lake water underneath of infinite extent.

The *frequency* at which the various dips occur for the reflection coefficient, such as ν_a, ν_b, ν_c, is a function of the snow depth and its refractive index (i.e., square root of the dielectric constant). The *depth* of the dip (maximum minus minimum amplitude) is a function of the dielectric constants of the snow, ice, and water, with only a slight dependence on the thickness of the ice layer or loss tangent of the snow. Because the dielectric constants of ice and water are quite well known for situations that would usually be encountered, the dielectric constant of the snow can be determined and related to the density. Using the snow dielectric constant, we can next determine the thickness of the snow layer uniquely from the value of the "dip frequency" ν_a. Having thus obtained the values of the density and thickness of the snow layer, we have the desired water equivalent of the snow layer.

We can also obtain the thickness of the ice layer, even though it is covered by the blanket of snow. This is shown by the lowest point in the curve of reflection amplitude versus frequency of Fig. 4, labeled ν_i. Similarly to the case of the snow layer, the frequency at which the minimum occurs is a function of the ice thickness and its refractive index, known to be 1.78 (plus or minus a few percent). Thus the thickness of the ice layer can be uniquely determined.

So far no mention has been made of the *phase* of the reflected wave. If two or more frequencies are employed simultaneously phase differences as well as amplitude differences of the reflected signals yield information regarding the various layer thicknesses, dielectric constants, and loss tangents. Although non-normal incidence of the waves is not readily accomplished, there may occur situations for which "bistatic" information could be obtained (i.e., transmitter and receiver in different locations, so that the waves are reflected obliquely). A discussion of these more complicated configurations is beyond the scope of the present paper.

Three-Layer Approximation

The principle of the electromagnetic interactions on which this paper is based can be approximately described in analogy with other systems that are well understood and widely used. Of course, one must realize that these explanations should not be compared too closely with experimental results that will be presented in the next section. In 1939, Blodgett [11] demonstrated the nonreflecting properties of a sheet of glass coated with a quarter-wave thickness of transparent material having a dielectric constant equal to the geometric mean of the dielectric constants of air and glass. As indicated in Fig. 5, medium 1 and medium 3 represent air and glass, respectively, with dielectric constants ε_1 and ε_3. The coating on the glass is medium 2, having dielectric constant ε_2, and thickness d. All three of the dielectrics are assumed to have zero conductivity. The amplitude reflection coefficients at the interfaces are r_{12} and r_{23}. We define $\alpha_2 = 2\pi/\lambda_2$, where λ_2 is the wavelength within the sheet. The reflection coefficient for the assembly is given by:

$$r = \left[\frac{(r_{12} + r_{23})^2 - 4r_{12}r_{23}\sin^2\alpha_2 d}{(1 + r_{12}r_{23})^2 - 4r_{12}r_{23}\sin^2\alpha_2 d}\right]^{1/2} \qquad (1)$$

which is derived in standard texts on electromagnetic theory such as Stratton [12].

To indicate the applicability of this simple three-layer system to the case of an ice layer over water, we now identify medium 3 to be water with a dielectric constant of 81. Medium 2 is a hypothetical material with a dielectric constant ε_2, including ice as one possibility. A plot of Eq. (1) is shown in Fig. 6, with thickness d of medium 2 plotted in units of λ_2, versus reflection amplitude of the combination. For ice thickness equal to a quarter-wavelength, the reflection amplitude is equal to 0.47. If medium 2 had a dielectric constant of 9, the reflection amplitude of the system would be zero, for the quarter-wavelength thickness.

Field Tests

To obtain experimental verification of the theoretical results, the arrangement indicated in Fig. 7 was employed. The sketch is intended to represent the electrical circuit block diagram and also the antenna configuration. The electrical circuit consisted of an oscillator and amplifier whose output was coupled to a transmitting antenna. The frequency of 290 MHz was not varied, and the power level was also held constant by coupling a portion of the signal to a Hewlett-Packard Type 415E meter whose reading was held constant by system gain adjustments. Two receiving antennas were connected to a "hybrid" that produced the vector sum of the antenna signals; this net output was measured by another 415E meter, yielding the "net receiver power." The three antennas were mounted on a wooden tower and spaced equidistant, 242 cm apart (8 ft). This arrangement was chosen so that the direct signal from the transmitter to each receiving antenna could be removed via the vector-sum process in the hybrid. The signal reflected by the snow layer and earth was received by both receiving antennas; however, because of the proximity of the lower unit, its signal was stronger than that obtained by the upper unit, so that the combination added to a net value in the hybrid.

As of the time of this writing, one test has been completed, having been conducted at a tower located at the Truckee-Tahoe airport (California). It consisted of holding the transmitted power at a constant level and at a fixed frequency and measuring the net receiver power as a function of snow-layer depth. The ideal situation would have been for a slow, steady snowfall to have occurred, with depth and density being physically measured while the electrical readings were being taken. Actually, at the time of the experiment there was very little snow in the vicinity of the test site. With the cooperation of the California Division of Highways, several truckloads of snow were delivered from Donner Summit to the site location, which the experimenters then shoveled so as to provide a snow layer of known depth, and having a cross section equal to that of the tower, namely, a square 242 cm (8 ft) on a side. The snow condition was changing with time, being quite moist on the first day, and progressively wetter during the next two days, when the test was completed.

The net antenna signal, in decibels relative to an arbitrary reference level, is plotted in Fig. 8 versus snow-layer depth. Two successive runs are shown, labeled moist snow and very wet snow. The data are quite encouraging, particularly inasmuch as the test is the first one for this system. The maxima and minima clearly represent the type of wave/layer interactions that the theoretical calculations have predicted. The "resonant" frequencies, at snow depths of 80 and 185 cm, are readily distinguished and are reproducible. The difference in the detailed shapes of the two curves, taken at different times, is not surprising, because the snow was changing its condition rather rapidly; in addition, the electrical parameters of the earth under the tower may have been different for the two runs. The dielectric constant for the very wet snow, being considerably higher than that of the moist snow, would represent a possible explanation for the relative peaks and dips of the curves at the 80 and 185 cm snow depths. The range of about 5 db from the maximum to the minimum for the moist snow curve indicates that adequate precision can be expected in this type of system, although it is premature to attempt to specify the precision at this time.

The point should be noted that the tower test program is intended mainly to confirm the general nature of the wave/layer interactions. The system is being modified to permit use of a range of frequencies to probe a given snow-layer depth, instead of the present system of maintaining a fixed frequency and varying the layer depth, although, of course, these two alternatives are mathematically equivalent. The use of a range of frequencies permits data to be obtained without disturbance to the snow in situ, which is an important consideration.

Assuming that the present series of tests involving fixed towers will provide adequate information, it is planned to make airborne tests, for which the experimental conditions will be much closer to the theoretical models. Flights over frozen lakes having snow layers would be of great interest; an abundance of such lakes are available in the Sierras. The model of Fig. 3 would apply quite well. The area sampled would be approximately that of the first Fresnel zone, or about equal to $D\lambda$, where D is the airplane height above the lake and λ is the wavelength at which the reflection is at a minimum. The electromagnetic system in a simple form could consist of an antenna that transmits a set of fixed frequencies, each during a pulse interval of about a microsecond. With the aircraft at an altitude of 150 meters or higher, the pulse containing a set of waves of a certain frequency would be completed before the echo signal from the earth surface would reach the antenna. Hence, the antenna at that time could be used as the receiver unit. Reflections caused by spurious factors in nearly all cases could be readily identified and removed.

The same type of measurement could be employed over reasonably flat meadows, if a set of "calibration" flights established the response in the absence of snow. Then, with snow layers present, a comparison of the response patterns could be correlated with the snow depth and density.

The use of the airborne system to measure the thickness of ice on the Great Lakes during the winter months would represent a logical application. Other similar uses in the arctic regions would merit consideration.

For certain situations it may be possible to consider a version of the flight system that is carried in a satellite. However, such an application would need to be based on adequate airborne testing in order to establish the required system characteristics.

Acknowledgments

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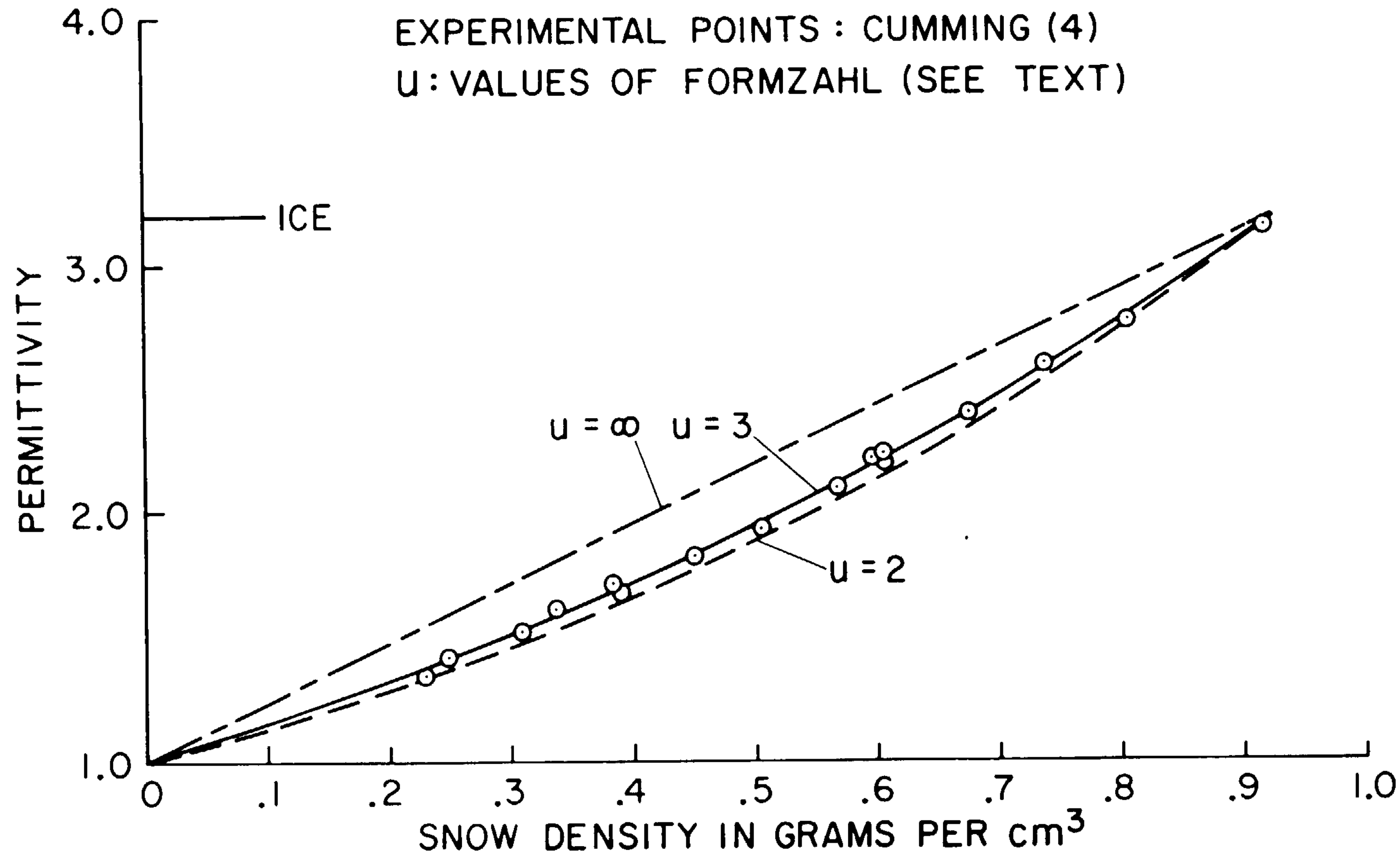

Fig. 1. Permittivity of Snow vs. Density

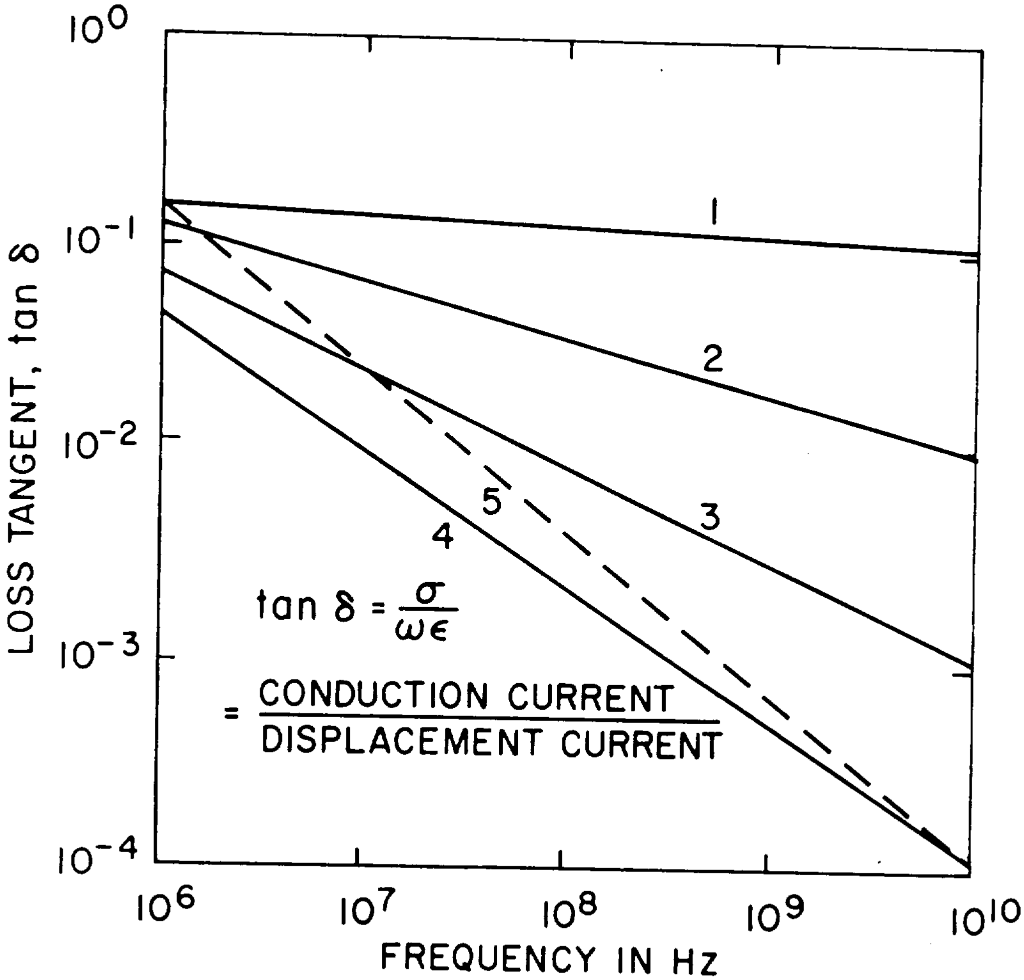

Fig. 2. Loss Tangent vs. Frequency for Various Snows

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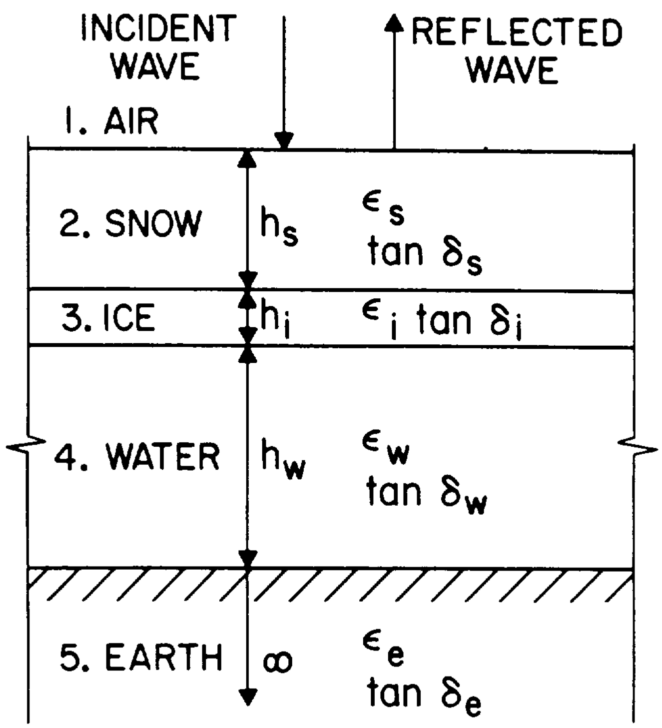

Fig. 3. Five-Layered Model

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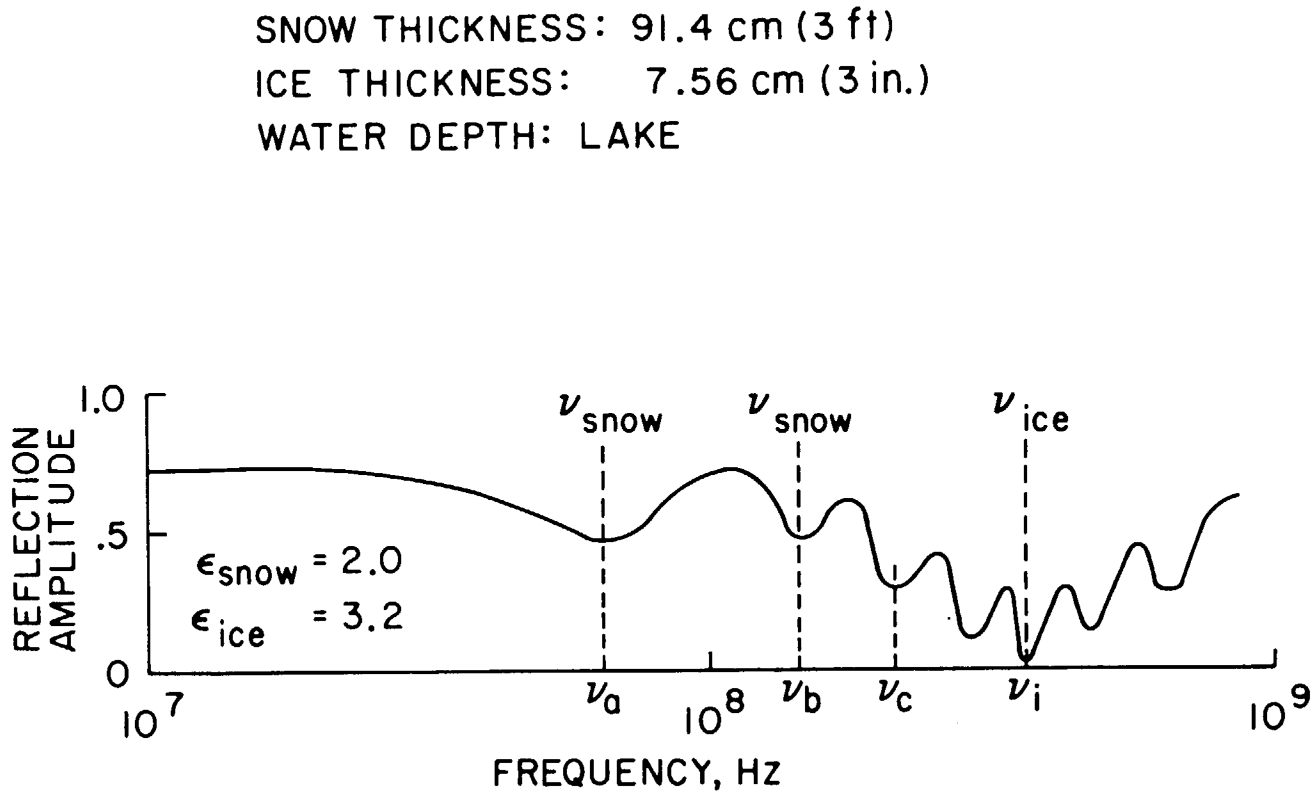

Fig. 4. Reflection Amplitude vs. Frequency

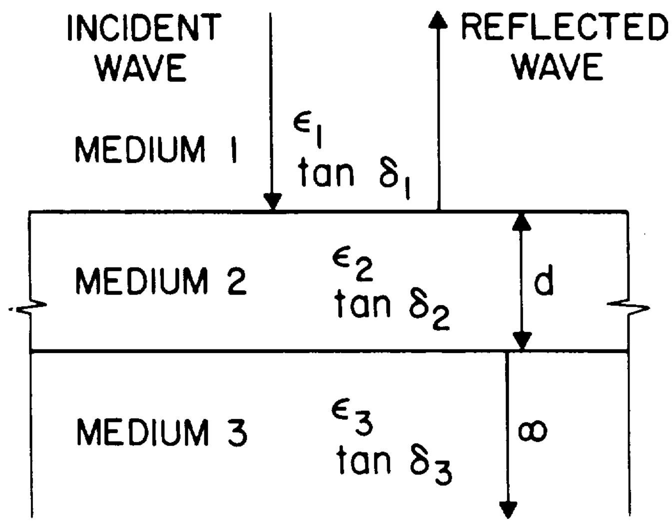

Fig. 5. Three-Layered Model

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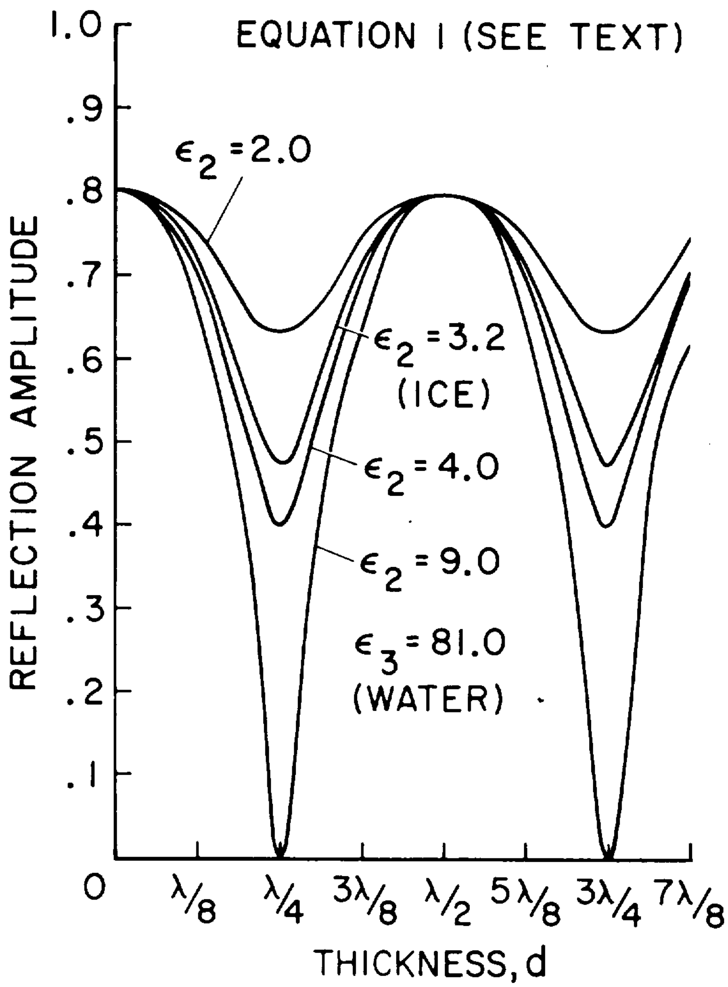

Fig. 6. Reflection Amplitude vs. Thickness

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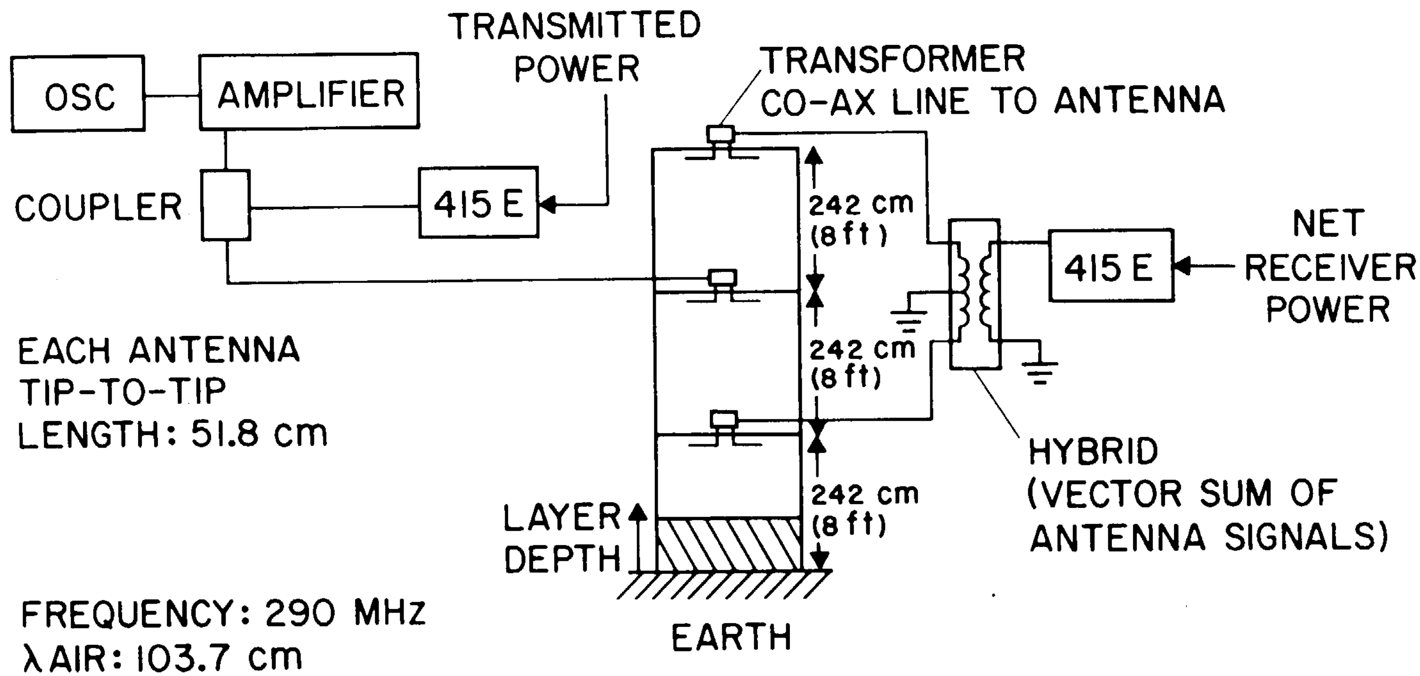

Fig. 7. Schematic Arrangement

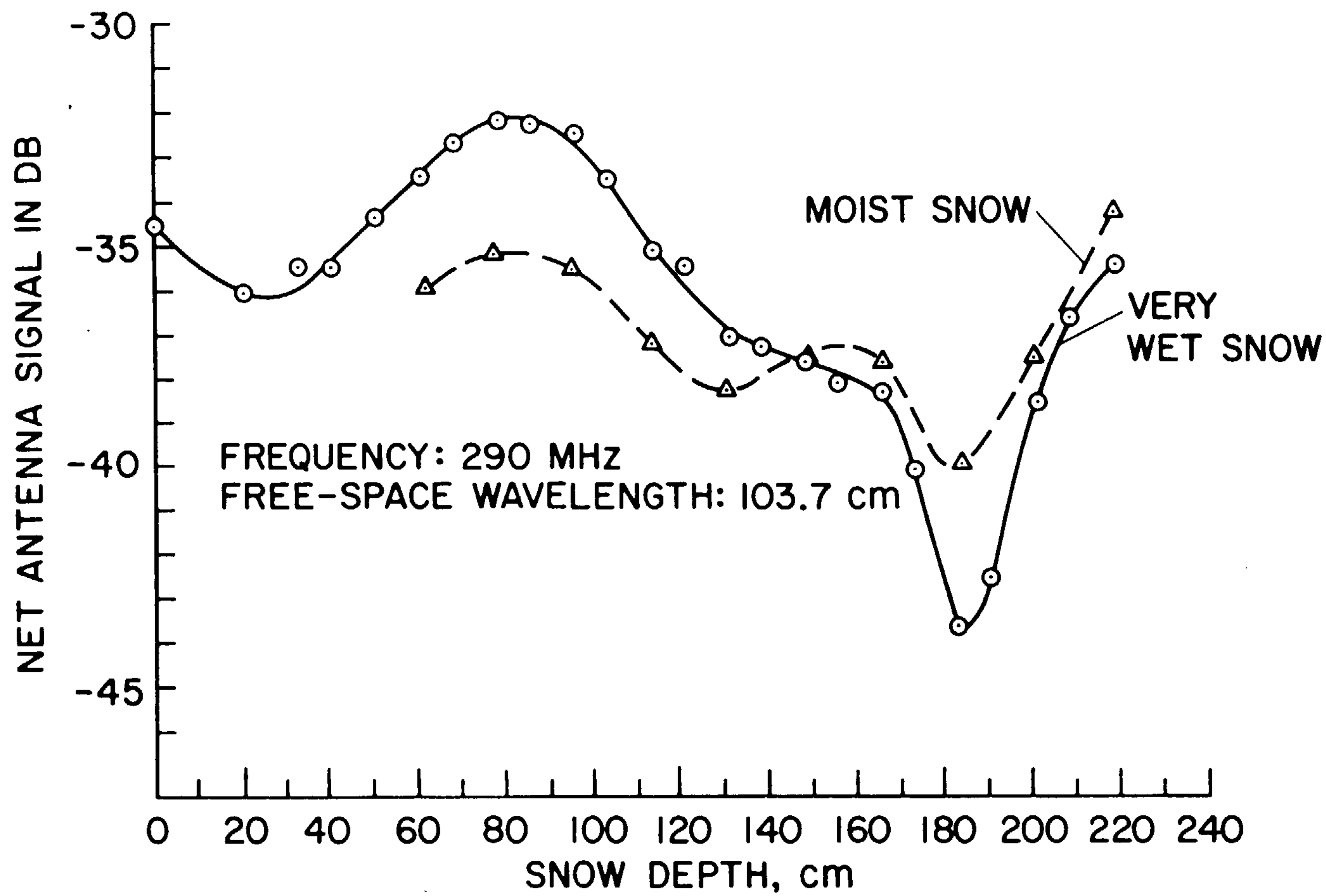

Fig. 8. System Response vs. Snow Depth

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